Assessing Control Loop Performance

If you're not keeping score of controller responses, you're only practicing.

Vance J. VanDoren, *Control Engineering*

The basic measure of a control loop's performance is the error between the process variable and its setpoint. Zero error indicates the controller's corrective efforts have been successful in forcing the process variable to match the setpoint.

However, size of the error at any given instant is not necessarily a good indication of how well the controller is performing. Some processes are naturally quiescent. Disturbances to the process variable and changes to the setpoint are uncommon in such cases, so the error remains zero for extended periods with little or no help from the controller.

Consider, for example, a controller that regulates the water level in a large reservoir. For the most part, the controller only needs to make minor corrections to the outflow through the dam to counteract effects of evaporation and precipitation upstream. Most any controller equipped with even the simplest error feedback mechanism could handle that job.

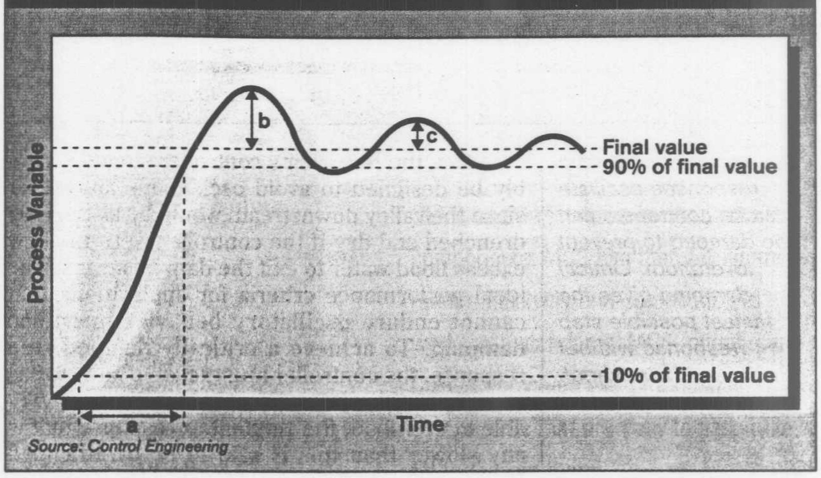
The real test of this controller's performance comes when a flash flood hits, causing the water level to rise precipitously. If the controller takes too long to compensate with an increased outflow, the reservoir may overflow. If it reacts too quickly, it may flood the valley below. The ideal controller for this application would perform somewhere between those two extremes.

Step tests

This example illustrates a more useful means of assessing a controller's actual performance level—the step test. A step test demonstrates how the controller reacts to an abrupt change in the setpoint or an abrupt disturbance to the process variable (such as a flash flood). Many PID controllers will react by forcing the process variable to oscillate as shown in the "Step Response" strip chart. The magnitude, frequency, and duration of the oscillations in this step response are commonly used to measure the controller's performance.

For example, decay ratio can be used to quantify how quickly the controller eliminates the process variable's oscillations after the initial step is applied. It is computed by dividing the magnitude of the second peak by the magnitude of the first. Referring to the "Step Response" chart, a low

Step Response



This strip chart shows how a typical PID loop forces the process variable to react when the setpoint is changed. A similar pattern may result from a disturbance, but the process variable usually ends up close to where it started since feedback controllers are generally designed to reject disturbances entirely. The rise time is a, the peak overshoot is b, and the decay ratio is c/b.

decay ratio indicates the controller can bring the process back into a steady-state or line-out condition quickly. John Ziegler and Nathaniel Nichols determined that a quarter wave (or 25%) decay ratio was low enough for their purposes and devised their famous PID tuning rules to achieve roughly that level of performance (See "Ziegler-Nichols Methods Facilitate Loop Tuning," *Control Engineering*, Aug. '98)

A lower decay ratio typically is achieved at the expense of a longer rise time during which the process variable rises towards its first peak. A long rise time indicates the controller is not particularly aggressive about responding to a disturbance or a setpoint change. On the other hand, the slow rise of the process variable reduces overshoot and minimizes the process variable's subsequent oscillations. The best controller for the reservoir would have to be reasonably fast, but not too oscillatory.

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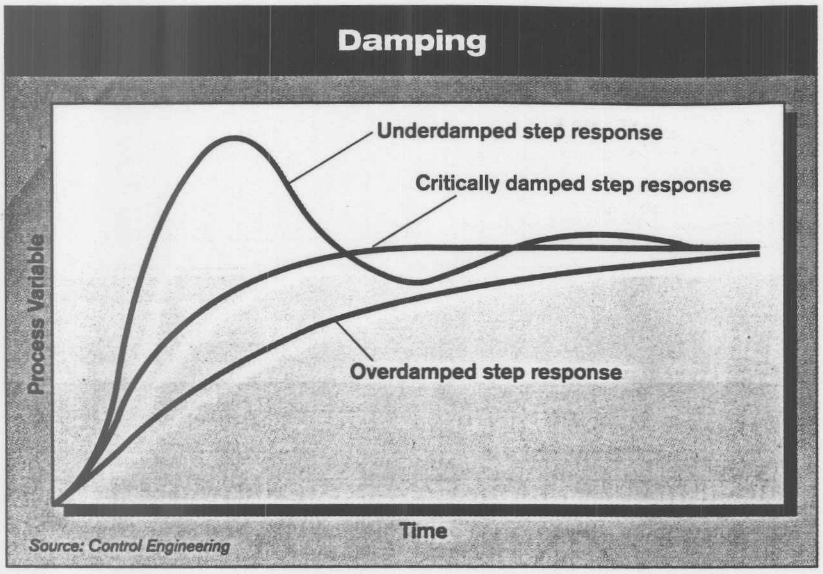
KEY WORDS

- Process control and instrumentation
- Loop tuning software
- Proportional/Integral/Derivative
- Process controllers

A basic measure of control loop performance is the error between process variable and its setpoint



Not all step responses oscillate since controllers can be damped to prevent overshoot. Critical damping gives the fastest possible step response without overshoot.

In fact, the reservoir's controller should probably be designed to avoid oscillations altogether since the valley downstream would be alternately drenched and dry if the controller were to allow excess flood water to exit the dam in surges. The ideal performance criteria for applications that cannot endure oscillatory behavior is critical damping. To achieve a critically damped step response, the controller must react to an error as fast as possible without causing the process variable to overshoot the setpoint. A response that is any slower than this is said to be overdamped while a response that is any faster (and therefore oscillatory) is said to be underdamped, see "Damping" graph.

Indirect performance measures

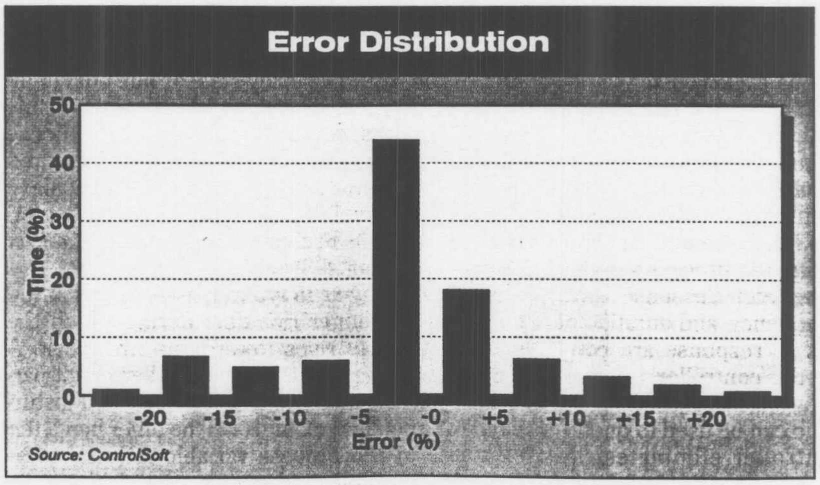
Step tests can reveal a great deal about a controller's performance, but they are not always practical. A control engineer probably wouldn't be allowed to flood the reservoir or abruptly change the desired water level just to see how the controller reacts.

Indirect computational techniques are often used instead. For example, ControlSoft (Cleveland, O.) has equipped the latest version of its InTune software with an error distribution chart that shows how long the error between the process variable and its setpoint has been very high positive, very high negative, almost zero, and so on; see "Error Distribution" chart.

No special test inputs are required. InTune simply collects real-time error data during normal operations and displays it as a histogram. The result is a statistical view of how well the loop has been performing in the recent past. If it shows the error has been almost zero 90% of the time, then the controller has been doing its job well. If it shows the error has been dwelling in several different ranges both positive and negative, then the controller has been causing the process variable to oscillate.

The next release of InTune will also include spectral analysis for identifying patterns in the process variable and the controller's output. Every stream of such data has its own characteristic "spectrum," which shows how it could be constructed from superimposed sine waves much as the spectrum of a light source shows its component frequencies. Like the spectra of similar light sources, the spectra of similar data streams show similar patterns of peaks and valleys when plotted.

Spectral analysis is particularly useful for assessing the performance of multivariable controllers that work to manipulate multiple process variables all at once. If the process variables interact, a change in one will affect all others. That can make the controller's job particularly difficult. However, a decoupling controller can be designed to coordinate its outputs so that each process variable can be manipulated more-or-less independently. The effectiveness of the decoupling effort will show up in the spectra of the process variables. Each should be different. If they show similar patterns, the decoupling has failed.

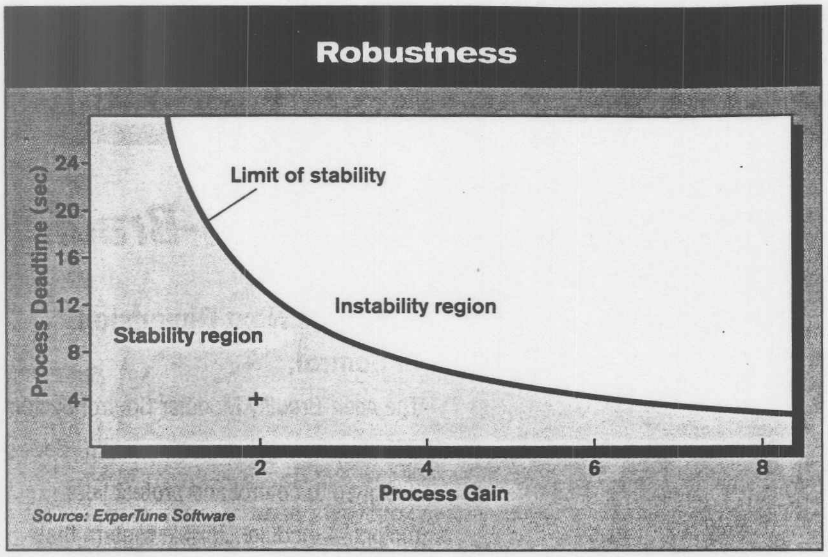


This chart shows how long the error between the process variable and its setpoint has remained in each of 10 ranges from "very high negative" to "very high positive."

Bode plots

A related analysis tool is the Bode plot which shows how much a controller amplifies each of the sinusoidal components of the error data and how much the process amplifies each of the sinusoidal components of the con-

Bode plots can be used to assess relative stability of closed-loop systems



This chart shows the range of first order processes that can be combined with a given PID controller to produce a stable closed-loop system. The red curve represents the controller's limit of stability which denotes the largest combinations of process gain and deadtime that this controller can handle. Combinations well within the stability region (such as the deadtime of 4 and gain of 2 shown by the cross) will be relatively more stable than combinations closer to the limit of stability. The larger the stability region, the more robust the controller.

troller's output. The Protuner software from Techmation (Scottsdale, Ariz.) can generate empirical Bode plots for the process and the controller from a file of historical process data. These show how well the controller and the process work together in a closed loop to amplify the desired frequencies and attenuate the unwanted frequencies.

Bode plots can also be used to assess the relative stability of the closed-loop system. If the system is unstable outright, its step response will oscillate with ever larger peaks as the controller tries to amplify the wrong frequencies too much. This makes instability easy to spot. However, a stable closed-loop system can also be on the verge of instability, which is almost as bad. What a Bode plot shows is how much more amplification the controller could afford to apply to the error signal without driving the process variable into oblivion. The Bode plot for a highly stable system shows a high gain margin; i.e., lots of room for additional amplification. For a less stable system, the Bode plot shows commensurately less gain margin. The gain margin is one of the most widely used measures of a controller's performance since it requires no special tests to compute.

Robustness plots

On the other hand, generating a Bode plot and reading its gain margin is not as simple as per-

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forming a step test and observing the overshoot or decay ratio. ExperTune from ExperTune Software (Hubertus, Wis.) offers a more intuitive alternative—the robustness plot. It shows the closed-loop system's relative stability by plotting the process deadtime vs. the process gain. The "Robustness" chart shows a sample robustness plot for a process with a deadtime of 4 sec and a gain of 2 (represented by the cross on the plot).

The red curve on the robustness plot represents the influence of the controller on the stability of the closed-loop system. Any process with a deadtime and gain that falls below or to the left of the red curve will yield a stable closed loop system when combined with this particular controller. Conversely, a process with a high gain and a long deadtime would correspond to a cross above the red curve and an unstable closed loop system.

A controller that is designed to be especially conservative will yield a red curve that encompasses a wide range of dead time and gain combinations; i.e., a large stability region. Such a robust controller could be combined with most any process to create a stable closed-loop system. Conversely, a more aggressive controller would have a relatively small stability region on the robustness plot, indicating that it would be stable only with processes with low deadtime and low gain.

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Tuning

The robustness plot illustrates the whole point of assessing a controller's performance—if it's too fast, too slow, too aggressive, or too conservative, re-tune it. This is generally a trial-and-error procedure. The control engineer designs a controller, tries it out, and keeps fiddling with it until the desired performance is achieved.

A robust controller could be combined with most any process to create a stable closed-loop system.

ACT GmbH (Tervuren, Belgium) combines those steps with a model-based controller called Topas that includes a performance-based tuning facility. Users can increase or decrease the closed-loop overshoot and the controller damping by manipulating those parameters directly. Topas automatically translates the user's specifications into the required tuning parameters. The closed-loop performance can be tuned for optimal setpoint response or for optimal disturbance rejection.

For more information about software products that can help translate performance measures into tuning parameters, see "How Software Tools Simplify Loop Tuning," (*CE*, Nov. '97). □

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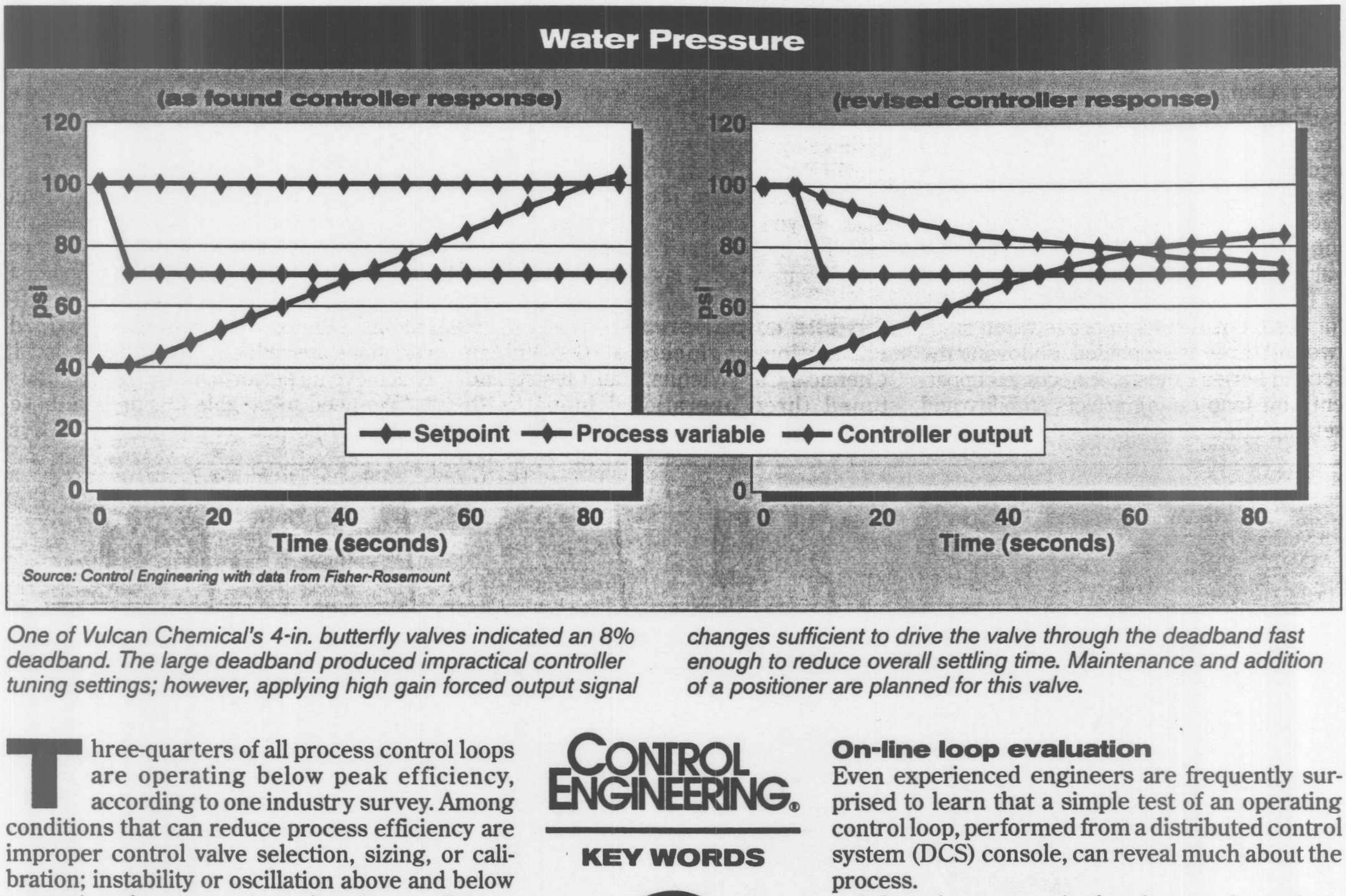
Open-Loop Response Testing Improves Process

75% of process control loops underperform: Here's how to evaluate problems and make improvements from the operator interface.

John Egnew, Fisher-Rosemount Educational Services



One of Vulcan Chemical's 4-in. butterfly valves indicated an 8% deadband. The large deadband produced impractical controller tuning settings; however, applying high gain forced output signal changes sufficient to drive the valve through the deadband fast enough to reduce overall settling time. Maintenance and addition of a positioner are planned for this valve.

Three-quarters of all process control loops are operating below peak efficiency, according to one industry survey. Among conditions that can reduce process efficiency are improper control valve selection, sizing, or calibration; instability or oscillation above and below a setpoint; slow response to changing conditions; or a combination of these factors. Approximately half of all loop problems relate to control valve performance, and the others are largely due to poorly tuned controllers.

Many production engineers, and even process control engineers, don't realize there is a way to evaluate the operation of individual control loops right from the control room. The open-loop response test, which is part of a three-step evaluation procedure, enables plant or refinery personnel to define the process by determining the process time constant, process gain, and process deadtime. Using these values, new controller settings can be calculated and applied. Resulting improvements in loop performance lead to better overall control of the process and enhanced productivity.

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KEY WORDS

- **Process control & instrumentation**
- **Calibration**
- **Education**
- **Loop controllers**
- **Process control valves**

On-line loop evaluation

Even experienced engineers are frequently surprised to learn that a simple test of an operating control loop, performed from a distributed control system (DCS) console, can reveal much about the process.

Selected processes in the plant can be evaluated, and the loop controllers can be tuned using values calculated from the test results. Techniques applied to "live" process control minimize the possibility of upsetting plant operations.

It is possible for users to tune controllers to minimize or eliminate process variable overshoot and produce predictable process variable settling times.

When computer simulations are used, field equipment performs flawlessly, but real-life loops can have sticking or improperly positioned valves that confound even the best-tuned controller. Working on live plant loops builds user confidence because class room teachings can be applied during hands-on sessions.

Using a DCS operator interface, a three-step process can verify, test, and tune a control loop.

Step one involves checking the valve or final

control device, including the positioner and other accessories, to be sure it's performing reasonably well. A valve deadband check can determine if it's performing adequately. If the valve does not react properly, conducting maintenance work must be evaluated, especially on valves that can significantly impact plant operations. Less significant valves can be tested and tuned, even if the valve is not operating properly, realizing that loop performance will not be optimized.

Step two is an open-loop response test that determines process time constant, process gain, and process deadtime. These values are used to calculate new gain and reset settings for the controller connected to that valve or final control device. Prior to conducting the test, signal filtering values and sample rate settings are assessed to ensure accurate test results.

Step three uses the data collected during step two to calculate new loop tuning values.

This three-step procedure is straightforward, but results improve when steps two and three are repeated. Following the second series of tests, it becomes apparent how loop tuning affects stability and settling time.

3-Step Loop Tuning

Step 1: Check the valve or final control device, including the positioner and other accessories.

Step 2: Open-loop response test determines process time constant, process gain, and process deadtime.

Step 3: Calculate new loop tuning values.

Repeat as necessary.

A frequently asked question is, "What about autotuning?" Many autotuning offerings are available to simplify tuning, but these algorithms do not always achieve optimum results. The three-step method makes attainment of performance goals more predictable and reliable. Relying totally on autotuning, especially on loops that continually wander away from setpoint, is not recommended.

On-site experience

Production engineers at the Vulcan Chemical Co. (Wichita, Kan.) tested and tuned three operational loops, with results shown in the table, Open-loop Response Test.

Documented results were achieved at operating conditions and valve positions existing at the time of testing. Other conditions and/or valve positions might produce different results, therefore a series of open-loop tests is recommended to obtain optimum performance across the expected operating range.

According to Rod Graf, production engineer and operational excellence supervisor at Vulcan's chlor-alkali plant, "We're implementing an Operational Excellence program designed to improve production efficiency in this plant and our other plants in Port Edward, Wisconsin, and Geismar, Louisiana. Obviously, control system stability is very important to the overall operational excellence of our plants."

For Vulcan, production efficiency means operating "closer to the edge" and requires optimizing each control loop. When too much variation or big swings occur in a process, a sizeable cushion must be provided for products to meet specifications. When overshoot is eliminated and variations are reduced, it helps each facility achieve its performance targets.

"We need to be able to stabilize these loops to optimize our processes," says

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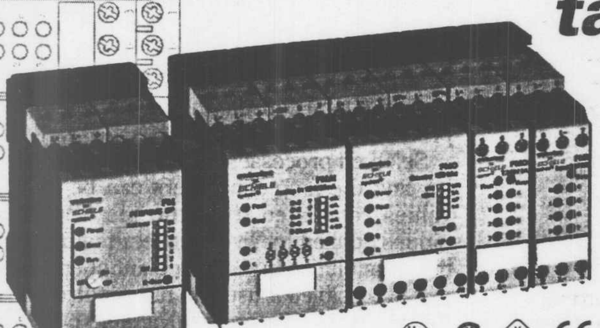

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Mr. Graf. "Sometimes, we become complacent with existing conditions. Changes to the test loops gave us all a better understanding of how the control system works and how we can influence the process. Now, when we begin the stabilization phase of our Operational Excellence program, we'll know what to look for and how to correct loop performance problems that may exist. This technique definitely has a practical value for us, and it's given us more confidence in our abilities to make a difference."

Individual loop stability allows optimization of the control system and has a positive impact on the overall process. Eliminating problems within individual loops helps improve production efficiency, and that's what makes open loop testing so valuable.

However, the real payoffs come when changes have a positive impact on overall operations. It's a good idea to select a measurable standard for documenting benefits of open-loop testing and closed-loop controller tuning. The standard can be different from plant-to-plant and depends on operational objectives. It could be increased throughput, reduced downtime, higher quality, greater financial savings, or any economic or performance factor. By establishing meaningful criteria, making measurements before and after loop changes are made, and comparing results you can fully realize the benefits of on-line loop evaluation.

Fisher-Rosemount Educational Services (Marshalltown, Ia.) conducts the "Process Control III" course on site, on live plant loops in hands-on sessions to "prove" these process improvements are possible. Vulcan engineers attended a three-day course. □

Open Loop Response Test

Process description	As found controller settings		Revised controller settings		As found settling time (minutes)	Revised settling time (minutes)
	Gain	Reset (repeats/min)	Gain	Reset (repeats/min)		
Temperature differential	0.75	0.3	2.5	0.8	10-15	5
Water pressure	0.5	1.0	1.5	1.0	10	4
Water flow	0.7	1.3	0.2	8.3	3-4	1

Source: Control Engineering with data from Fisher-Rosemount

In each loop, process variable settling time improved significantly, and overshoot of the process variable was not a factor. Revised controller settings are the results of the first pass test; additional improvement would likely be obtained by repeating the test.

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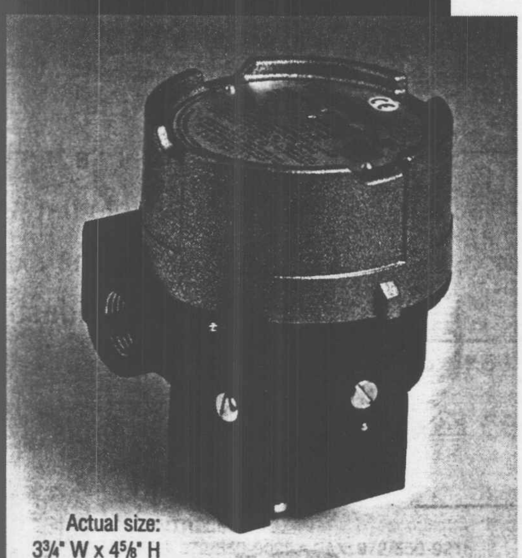

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